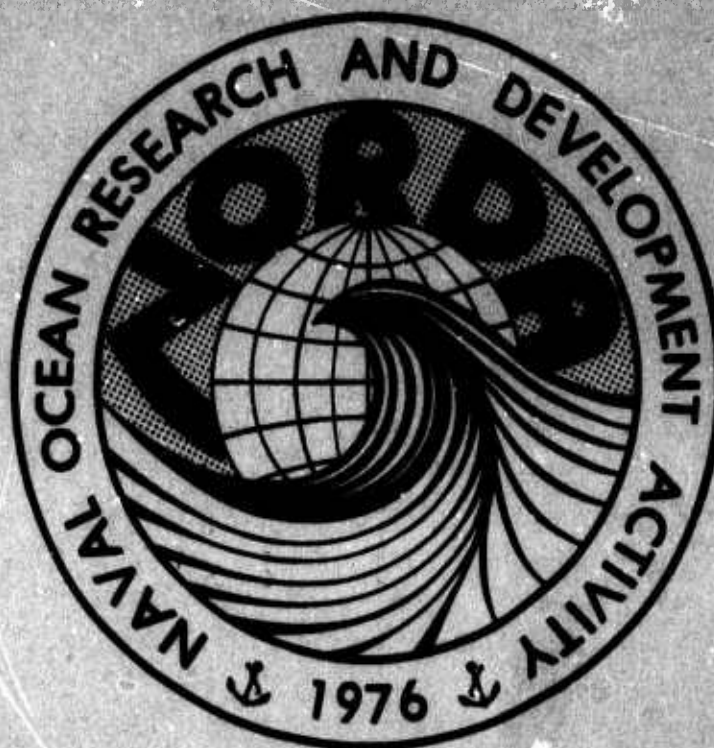


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Naval Ocean Research and
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A Preliminary Assessment of Soviet Development of Optimum Signal Discrimination Techniques: Optimum Space-Time Processing



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A PRELIMINARY ASSESSMENT OF SOVIET DEVELOPMENT OF
OPTIMUM SIGNAL DISCRIMINATION TECHNIQUES:
OPTIMUM SPACE-TIME PROCESSING

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October 1987

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A PRELIMINARY ASSESSMENT OF SOVIET DEVELOPMENT OF
OPTIMUM SIGNAL DISCRIMINATION TECHNIQUES:
OPTIMUM SPACE-TIME PROCESSING

SUMMARY AND CONCLUSIONS

This study provides an overview of Soviet work in the subject of optimum signal discrimination techniques. Its purpose is to aid U.S. scientists in becoming more familiar with an extensive signal processing effort of which they undoubtedly have had little prior awareness. It provides general substantive comment and bibliographic resource materials.* If this work is successful in accomplishing its goal, it will serve as an example of a reverse technology transfer.

The Soviets have, for several decades, taken a more rigorous statistical approach to the study of oceanic processes and the theory of detection signals in the ocean environment than has the United States. The Soviets view this environment as non-Gaussian, nonstationary, and non-white, and do not avoid the complications this presents to the formulation of the theory of optimum signal detection and estimation. There appears to be poor U.S. access to this work. The United States would probably benefit from selected uses of Soviet theory and algorithm developments in this topic.

Soviet development of optimum signal detection and estimation techniques is broadly based, covering various aspects of radar, sonar, and communications. They have an extensive program in the development of optimum space-time processing (OSTP) and have extended the theory further than

*A more extensive set of bibliographic resource materials on this subject can be found in "Soviet Approach to the Development of Optimum Signal Discrimination Techniques: A Data Listing," Radian Corporation Report 131-740-01, April 1982.

has the U.S. Their effort is based on the Karhunen-Loeve expansion extended to nonstationary space-time signals and noise. Possibly to support requirements to develop detection equipment for use in realistic environments, the Soviets expend considerable effort in selected aspects of measuring and modeling space-time correlation functions of the noise environment.

Although their fundamental formulation is based on U.S. work of the early 1960's, their specific work has been greatly different from that of the U.S. Much of the Soviet work has been in the development of specific algorithms. Some of their more recent efforts appear oriented toward realistic sonar problems and there appears to be connections of this work in algorithm development to the development of special architecture processors, including optical processors.

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A PRELIMINARY ASSESSMENT OF SOVIET DEVELOPMENT OF
OPTIMUM SIGNAL DISCRIMINATION TECHNIQUES:
OPTIMUM SPACE-TIME PROCESSING

1.0 GENERAL SOVIET DEVELOPMENTS IN STATISTICAL DETECTION
 THEORY

The Soviets have long emphasized a rigorous statistical treatment in the analysis of stochastic phenomena. They are, for example, widely recognized for contributions in the analysis of turbulence processes and propagation in random media. Recent detailed attention to their research and analysis in ocean science reveals better the depth with which statistical concepts make up their basic view of nature. Just as Soviet scientists are more strongly inclined than are U.S. scientists toward an analytical approach to the study of physical phenomena, they are also more strongly inclined to base their analyses on rigorous statistical formulations.

Virtually all Soviet ocean science has a strong basis in statistics. This includes routine oceanographic data acquisition based on optimum sampling schemes and the use of more sophisticated statistical models to describe the data, special hydrodynamic studies treating inhomogeneity and nonstationarity of the fields, the full range of underwater acoustics research, and optimum signal discrimination research.

The Soviet work is based strongly on their view that real processes taking place in the ocean are non-Gaussian, nonstationary, and non-white and they do not avoid treating these processes as such. They place a strong emphasis on correlation analysis, but because they view ocean processes as nonstationary, they have often used structure functions in the analysis of such processes. We have often observed the fact that the Soviets do not emphasize the use of Fourier transformation to the extent that the U.S. does. We do not often recognize, however, that the Soviets

do so largely because they do not concede stationarity as the general order of things and often deal with short observation periods.

The Soviets have a strong and well-recognized school of statistical channel modeling. Preeminent in this field is V. V. Ol'shevskiy of the Acoustics Institute of the USSR Academy of Sciences in Moscow. This school has organized several continuing symposia, the most extensive of which is the All-Union School Seminar on Statistical Hydroacoustics. This symposium has met annually since 1971. For eight of those years the symposia's proceedings are available in English. The Statistical Acoustics Ocean Modeling Seminar is another symposium series sponsored by this school of thought.

Work coming out of this statistical school is broadly based in all aspects of underwater acoustics research including strong scattering, signal fluctuation and coherence, and reverberation research. A good example of the Soviet effort is Ol'shevskiy's own work. Ol'shevskiy emphasizes a point-scattering model that is the greater part (by virtue of its apparent long-term and continuous support) of the FOM (Faure, Ol'shevskiy, and Middleton) approach. Much of Ol'shevskiy's and associates' work is best related to active sonar and UWC. Ol'shevskiy, in addition to writing a very large number of papers related to statistical acoustics, wrote the well known book Statistical Methods in Sonar.

Also heavily reported in statistical acoustics seminars is work concerning optimum signal discrimination in realistic environments. This work, as applied to sonar, is generally led by N. G. Gatkin of the Kiev Polytechnical Institute but is broadly based in several institutes and includes acoustics and electromagnetic signal processing.

Although several leading groups in the field publish extensively on topics of optimum and adaptive space-time processing, their work has not been recognized or used in the West. This situation is due to relatively poor Western access to the journals and symposia proceedings in

which their works are published. (To a certain extent this lack of attention may be due also to lower emphasis on statistics in U.S. research programs.) The Soviet Physics-Acoustics Journal--the Soviet journal followed most closely by U.S. acousticians--has not published a great deal of Soviet work in signal processing.

The Soviets show a clear appreciation for the problem of detecting signals in environments for which a priori knowledge of their distributional properties is lacking. When attempting to deal with these problems they emphasize realistic data representations to an extent not done in the U.S., and they attempt to develop nonparametric detectors. There are indications, for example, that simple devices and algorithms might exist for dealing with nonstationary noise fields and for CFAR (Constant False Alarm Rate). They, to a larger extent than the U.S., integrate oceanic data into higher order stochastic models. They have a broad, cohesive effort to understand environmental effects upon signals and the detection process.

The Soviets have long lagged the U.S. in an inclination to implement their more sophisticated mathematical treatments into hardware. Consequently, they have lagged in the development of sophisticated hardware to perform routine processing tasks. They had an early interest in adaptive techniques to achieve optimality in processing but here, especially, they have been limited in what they could achieve. They recognized early that they must make approximations to arrive at hardware designs they could implement. Often this meant that they would separate spatial processing from temporal processing just as the U.S. does routinely. However, on some occasions they adopted quasioptimal designs in which separation was not forced.

2.0 EARLY FORMULATIONS OF THE OPTIMUM SPACE-TIME PROCESSING PROBLEM

It should be recognized that the formulation by Fal'kovich in 1965 (66F001)* was a major contribution to OSTP. Fal'kovich's work is cited extensively in Soviet literature, but reference to it is lacking in Western literature. His work combined the more narrowly defined works of Shirman (61S001) and Kuriksha (63K001) into the basic formulation of the Soviet approach to OSTP. Most of what followed were refinements to his work, the application to special cases, the development of specific algorithms, and the formulation of adaptive techniques to approach OSTP.

The original works of Shirman (61S001), Kuriksha (63K001), and Fal'kovich (66F001) were based on an extension into space and time of the work of Middleton, Woodward, Karhunen and Loeve, and Davenport and Root. Shirman develops the case for optimum resolution with a long, narrow slit. Background interference is EM thermal noise and radioastronomy is probably the application Shirman had in mind for that work. Kuriksha considers a wide class of two-dimensional antenna systems. He probably had more general applications in mind than Shirman. The work probably is related to radar. Kuriksha's development is an adaptation of a development by Middleton about five years earlier. Kuriksha extended the work to multidimensions. In addition to resolving power, Kuriksha develops formulation for the accuracy of measurement of angular coordinates and the detection of point and extended targets. Kuriksha's work was limited by the difficulty of application of his formulation to engineering practice and the problem of acquiring an a priori measure of the 3-dimensional correlation function of the interference.

*This reference code is discussed in "Soviet Open Literature Document Management Facility: Volume III Microprocessor Based System," Radian Corporation Report 261-005-09, April 1982. The citations coded in this manner in this report are found in the REFERENCES section.

By 1965 only the above two articles (either Soviet or Western) had been published on Optimum Space-Time Processing when Fal'kovich (66F001) undertakes the task of completing the ground work for OSTP. Here he bases his development on the likelihood ratio extended to multidimensions. Although not cited, the development is the Karhunen-Loeve formulation extended to space-time. This development provides a filter function for the optimum space-time receiver represented as a solution to an integral equation. The filtering process generates a test statistic which is the log likelihood ratio. The useful results of the formulation is the generalized ambiguity function expressed in space and time. A decision concerning the presence or absence of a signal is according to the Bayes approach.

The next stage of development of OSTP for application to EM problems was carried out by Chernyak (73C001 and 74B014) and Kuz' (75K025 and 75K027). Some of their original work dates to the late 1960's. Chernyak seems concerned with implementation of OSTP theory and seeks cases where it will simplify (some involving separating space and time optimizations, and some not). In 73C001, Chernyak lays out the conditions under which OSTP will separate into optimum spatial processing (OSP) followed by optimal temporal processing (OTP). He states that both of the following conditions must apply: (1) the difference between time delays of the signal and interference delays at the various elements of the array must be much less than the inverse of the spectral width of the signal and (2) the spectra of all interferences within the signal bandwidth must be the same at the various receiving elements. He states that condition 2 can be relaxed in strong interference. The conditions are satisfied best for narrowband signals and small apertures. These conditions suggest that the U.S. should exercise care in its practice of separate adaptive beamforming followed by adaptive filtering in cases of broadband detection, narrowband detection with very wide apertures, interarray processing, and environments containing weak interference and multipaths.

The work to this point has been discussed in terms of EM wave propagation, signal detection, and parameter estimation in such fields as radar and radioastronomy. However, the work quickly found applications in communications. In 1971 Klovskiy and Soyfer (72K008) extended OSTP to these cases and in 1976 wrote a book on the subject.

Of primary interest here, however, is the contemporaneous work that was being conducted by the Chair of Acoustics and the Kiev Polytechnical Institute extending the work to sonar application. The extremely prolific work of N. G. Gatkin, who has held the chair since the 1960's, and his proteges will be considered next.

3.1 INITIAL DEVELOPMENTS OF THE CHAIR OF ACOUSTICS KPI

The Chair of Acoustics at the Kiev Polytechnical Institute has contributed a great deal to the Soviet development of optimal space-time signal processing theory. Basic work started in the mid-1960s in the temporal dimension only. Through the 1970s, however, its work dealt with progressively more difficult problems in full space and time. In 1970, Gatkin published a benchmark paper (70G004) which seemed to collect together all his efforts prior to that time. This work appears to have been his point of departure into space-time processing.

This work is based on the Karhunen-Loeve expansion as developed by Davenport in 1960. However, Gatkin proceeds to develop algorithms based on numerous specific cases of the solutions of the resulting integral equations. The general method for the solution was developed by Gatkin in a paper that is not available at the time of this review. Gatkin discusses the technique, which he calls the "method of envelopes," briefly in 70G004. Unfortunately, the method is good only in the narrow-band case. Following this paper very closely, Gatkin, O. B. Galanenko, and L. G. Krasnyy wrote a paper on optimal space-time processing of signals in a Gaussian noise field (71G003). This paper seems to set the tone for the next decade of Gatkin's work.

The basic formulation of Gatkin's work is a multi-dimensional extension of the K/L formulation. The optimal space-time processor is given as the solution $b(t, \bar{x})$ of the integral equation

$$\int_T \int_{\Omega} k(t, t'; \bar{x}, \bar{x}') b(t', \bar{x}') dt' d\bar{x}' = s(t, \bar{x})$$

where $k()$ is the space-time correlation function of the noise field and $s(t, \bar{x})$ is the signal. T and Ω are the observation interval and the spatial region of observation, respectively. Because T and Ω are finite, the orthogonal basis set into which $b()$ and $s()$ can be expanded is not Fourier functions. For this reason, the Soviets do not, in general, take the Fourier transform as an initial step in a processor implementation as is usually done in the United States.

In all of this Soviet work, the Soviets tend to treat each conceivable case in great detail. They develop complete analytical solutions and provide algorithms for processing the input space-time field to arrive at a value of the maximum likelihood ratio (MLR). They use the MLR formulation extensively in these problems. (In non-Gaussian problems, they often seek a generalization of the MLR approach.) This formulation leads to a form of a matched filter processor extended to space-time and applicable to nonwhite, nonuniform, and nonstationary noise fields. In 1973 (73B006), Gatkin et al. considered these aspects in greater detail and again provide analytical solutions and algorithms for specific cases.

In these papers and in others of that period, the Soviets conclude that in some cases, e.g., wideband noise, the structure of the optimum processor requires joint processing in space and time. They suggest on several occasions that comprehensive studies of the space-time correlation function of the noise field are required to support development of optimum space-time processors. They point out that OSTP can provide significant gain (36 dB in one cited case) over the nonoptimal processor. Unfortunately, the Soviets do not give any examples of the gain achieved by OSTP versus that achieved by separate optimum processing in space (OSP) followed by optimum temporal processing (OTP); i.e., optimum beamforming followed by optimum filtering. This potential gain might be determined, however, by a closer look at, and possibly implementation of, the Soviet-developed algorithms.

One Soviet paper (73G004) appears to be a collection of the algorithms that they had developed through the early 1960s. Over ten equations and diagrams of optimum space-time processors are given. It might be of some value to implement and test some of the algorithms they present.

3.2 WORK EXTENDING OSTP TO NOISY SIGNALS

The Soviets did not delay efforts to move into more complex situations. Beginning as early as 1971, they extended their space-time formulation into the area of noisy and fluctuation signals (71G005). This paper provides for a specific form of fluctuation, but later papers generalized on it.

The general formulation as given in 73G004, 73G005, 73G010, and 74G012 require the solution of two integral equations involving the space-time correlation functions of the signal and the noise separately and combined. The requirement for a priori information is severe and the equations are complex. However, the Soviets develop several specific cases and provide for analytical solutions. Some cases may seem a bit contrived, but their applicability remains to be tested outside the Soviet Union. The Soviets would likely carry these extensive theoretical developments over into their own experimental programs, but there is little published information to confirm this.

The Soviet approach to OSTP of fluctuating signals results in a formulation that is an extension of the Woodward ambiguity function. The solution gives the MLR as

$$U_0 = \frac{1}{2} \int_T \int_{\Omega} \int_T \int_{\Omega} u(t, \bar{x}) u(t', \bar{x}') H(t, t'; \bar{x}, \bar{x}') dt dt' d\bar{x} d\bar{x}'$$

where $u()$ is the input field and $H()$ is the optimum filter determined by the solution of the previously mentioned integral equations.

In the case of a discrete hydrophone array of N elements, the equation becomes

$$U_0 = \frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N \int_T \int_T u(t, \bar{x}_i) u(t', \bar{x}_j) H(t, t'; \bar{x}_i, \bar{x}_j) dt dt'$$

3.3 WORK EXTENDED TO SEPARATE ARRAYS AND MULTIPATH ENVIRONMENTS

Since 1974 the Soviets have continued their OSTP development to include mutual processing of multiple arrays. In addition to Gatkin, L. G. Krasnyy and S. V. Pasechnyy, both proteges of Gatkin, play significant roles in the development. However, it seems to be Pasechnyy who is becoming the dominate figure in this complex area. Moreover, his work seems clearly oriented toward the development of algorithms for sophisticated mutual processing of sonobuoy arrays. Selected papers on the subject which include Pasechnyy as an author are 74G013, 75G014, 76G026, 77G036, 78G007, and 79B024.

In one case (75G014) involving up to six arrival paths each with Rayleigh amplitude and uniform phase fluctuations, 5 to 10 dB gain is demonstrated with the Soviet technique. Later the Soviets considered adaptive techniques in situations where the multipath structure is not known a priori (77G036).

With recent trends in Soviet development of special architecture processors, as well as a general relative rise in Soviet digital technology, the Soviets may begin to implement their sophisticated analytical capabilities into advanced hardware. The Soviets have pursued a special area of work involving the following four lines of research and development:

- Reorganizable Associative Parallel Array Processors, as the Soviets refer to it;
- Optoacoustic devices for control and computing relating to their array processors;
- Residue Class Number Systems (RCNS) used in array processors; and
- Generalized orthogonal transformations done on array processors.

Each of these areas has been researched independently of the others by the Soviets. Of concern, however, is recent Soviet work linking all of them together into special computing architectures. And of special interest in this study are links between work in the above topics and optimum space-time signal processing development.

In this latter category of effort is that of a prolific research group possibly led by I. Ya. Kremer. Workers with Kremer include V. A. Pon'kin, G. S. Nakhmanson, V. G. Radziyevskiy, and possibly N.A. Potapov. The affiliation or affiliations of this group is presently unknown. Papers by this group include 75K024, 76P016, 77K068, 78K032, 78K041, 79N004, 80N005, and 80P006. In addition to OSTP in signal detection this group also works on problems of optimal estimation. While it is not certain whether their interests center on EM, on acoustic problems, Nakhmanson has published on specifically acoustical topics.

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8. JPRS L8364: Works on the 8th All-Union School Seminar on Stat. Hydroac's
9. JPRS L8825: Works of the 9th All-Union School Seminar on Stat. Hydroac's
10. REEP: Radio Engineering and Electronic Physics
11. SAC: Soviet Automatic Control
12. TCRE2: Telecommunications and Radio Engineering, Part II

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The Soviets have, for several decades, taken a more rigorous statistical approach to the study of oceanic processes and the theory of detection signals in the ocean environment than has the United States. The Soviets view this environment as non-Gaussian, nonstationary, and nonwhite, and do not avoid the complications this presents to the formulation of the theory of optimum signal detection and estimation. There appears to be poor U.S. access to this work. The United States would probably benefit from selected uses of Soviet theory and algorithm developments in this topic.

Soviet development of optimum signal detection and estimation techniques is broadly based, covering various aspects of radar, sonar, and communications. They have an extensive program in the development of optimum space-time processing (OSTP) and have extended the theory further than has the U.S. Their effort is based on the Karhunen-Loeve expansion extended to non-stationary space-time signals and noise. Possibly to support requirements to develop detection equipment for use in realistic environments, the Soviets expend considerable effort in selected aspects of measuring and modeling space-time correlation functions of the noise environment.

Although their fundamental formulation is based on U.S. work of the early 1960's, their specific work has been greatly different from that of the U.S. Much of the Soviet work has been in the development of specific algorithms. Some of their more recent efforts appear oriented toward realistic sonar problems and there appears to be connections of this work in algorithm development to the development of special architecture processors, including optical processors.

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